East & Thayer

Investigation of the practicability of the half frequency generator

Electrical Engineering

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INVESTIGATION OF THE PRACTICABILITY OF THE HALF FREQUENCY GENERATOR

BY

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AND

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THESIS

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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ENTITLED INVESTIGATION OF THE PRACTICABILITY OF THE HALF FREQUENCY GENERATOR

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

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AN INVESTIGATION

OF THE PRACTICABILITY

OF THE HALF-FREQUENCY

GENERATOR

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AN INVESTIGATION
OF THE PRACTICABILITY
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GENERATOR

Among modern prime movers the steam turbine occupies a leading position due to its economy, compactness, and superior operating qualities, but some of its characteristics have imposed special burdens upon the designers of steam turbine driven generating machinery. Perhaps the most serious problems are those incident to the use of high rotative speeds found in the turbine. Electrical requirements as to frequency and voltage must be carefully considered along with the severe mechanical stresses resulting from centrifugal force. The best economy in any turbine, except very large ones, is had at speeds of not less than 1500 revolutions per minute, and for a frequency of 25 cycles this requires a two pole generator. Now a two pole revolving field structure is one in which the iron and copper arenot economically used, since there is of necessity so much idle space. Since for commercial power circuits a frequency of 25 cycles is almost universal it is important that there be available an alternator combining good construction and suitability for high turbine speeds.

The half-frequency generator seems to satisfy both these conditions. It is in construction similar to a slip ring induction motor, and is driven at twice synchronous speed in the direction in which it runs as a motor. Under these conditions there are set up in the rotor, electromotive forces of the same frequency as those impressed on the stator, and if these electromotive forces are of the same value as those in the stator, the rotor may be paralleled with the stator and made to deliver electrical energy. This machine can furnish only in-phase current and must be supplied with a leading magnetizing current from an outside source, such as a synchronous generator in parallel or a synchronous motor or convertor. The proprotion that this exciting current bears to the energy current output of the half-frequency generator determines the value of the device as a piece of commercial apparatus, as it is obvious that if it requires an excessive exciting current the equipment to supply such current must be large and expensive. It has been the purpose of this thesis to determine by laboratory experiments the current relations of the half-frequency generator under various conditions of operation.

GENERAL THEORY

Since the construction of a half-frequency generator is similar to that of a slip-ring induction motor the theory of the latter may be used. At stand-still the slip is 1.0 and the electromotive forces in the rotor are the same as in the stator; as the motor speeds the slip approaches zero and the frequency of the rotor current decreases. If now, the machine be driven mechanically by an outside source in the same direction above synchronous speed, the slip

becomes negative and the rotor frequency begins to rise, with the phase rotation in the opposite direction from that in the stator. At a little above synchronous speed we have the induction generator in which the load is increased by raising its speed. As the speed continues to rise, the rotor frequency increases, until at twice synchronous speed the rotor conductors are going just twice as fast as the revolving field set up by the stator currents. The rotor and stator frequencies are then the same and if of the same voltage may be paralleled when one pair of rotor leads is reserved to make the phase rotations occur in the same direction. At this point the reason for the name, half-frequency generator, becomes apparent: the frequency is half that which would be given by a synchronous generator of the same number of poles and at the same speed. At twice synchronous speed the rotor currents set up a flux that sweeping past the stator conductors induces currents in them and magnetically transfers part of the power from the mechanical source to the stator which in its turn delivers electrical energy. The induction motor has thus become a half-frequency generator, the moving and stationary parts of which both deliver power, altho an external leading wattless current is required for excitation.

This last statement means that the generator can supply power only to a circuit that takes a leading current of proper magnitude to supply the excitation. If the amount of load changes, its power factor must change so that the leading wattless current will remain unaltered, except, of course, as it changes with the load on the generator. If it is desired to feed a non-inductive circuit as, for instance, incandescent lamps, the leading current must be furnished by a second machine that may be a synchronous generator, or synchronous motor or convertor. If the half-frequency machine is to

supply power to an inductive load, the leading current furnished by the exciter must be great enough to compensate f or the lagging wattless current of the load as well as deliver the leading wattless current for excitation.

THE APPARATUS USED.

The machine used as the half-frequency generator in these tests was a 7.5 kilowatt 60 cycle, 3 phase alternator No. 94227, of the General Electric Company of Schenectady, Type AHB, class 6-7.5-1200, Form A. At a speed of 1200 r.p.m. the machine was rated at 20 amperes at 220 volts. The regular revolving field of the alternator was removed, and replaced by a wound rotor structure that fitted interchangeably with the field. All the alternating current apparatus was worked three phase, the stator of the machine being connected in delta. In the combination used, the ratio of the stator turns was not one to one, but was of such a value that when running at twice synchronous speed with 68 volts at 30 cycles impressed upon the stator, the pressure between slip rings was 38 volts.

To bring these voltages together that the rotor and stator might be paralleled it was decided to step up the rotor electromotive force by the use of a bank of three auto-transformers. For this purpose there were used three, 1 kilowatt, core type "Packard" transformers made by the New York and Ohio Company, of Warren, Ohio, for distributing service at 550 and 110/55 volts. Each transformer had two low tension coils of 110 turns each,so there were wound on the core 29 turns of #8 double cotton covered copper wire, connected between the two regular coils. Then a lead was brought out from

one of the junctions so that one regular coil and the extra turns were included, to give 38 volts while the voltage over all three was 68 volts; thus

$$\frac{110 + 29 \text{ turns}}{110+29+110 \text{ turns}} = \frac{139 \text{ turns}}{249 \text{ turns}} = \frac{38 \text{ volts}}{68 \text{ volts}}$$

The three transformers, altered in this way, were connected in Y as in Fig. 3, Page 13.

In circuit between the rotor and stator was a three pole synchronizing switch with three synchronizing lamps permanently connected between the terminals.

The half-frequency generator was driven thru a belt by a 5 horse power Westinghouse 4 pole, shunt wound, 125 volt, 1600 r.p.m. motor, No. 53471.

For supplying the leading exciting current there was used a synchronous generator precisely similar to that used as a half-frequency machine with the exception that the regular 6 pole revolving field was used. The field terminals were brought out to slip rings that were supplied with direct current from the power house bus bars. The windings of the generator were connected in delta.

This synchronous generator was belt driven by a four pole shunt motor made by the Bullock Electric Manufacturing Company of Cincinnati and rated at 15 horse power at 1100 r.p.m. at 220 volts. For the sake of obtaining a lower speed the field was excited with current at 220 volts while the armature was supplied from the 110 volt bus bars.

Part of the testing was done with the aid of a small double current generator of the General Electric Company. This machine was designed for 7.5 kilowatts at 110 volts on the direct current side when running at 60 cycles, or 1800 r.p.m. Armature leads brought out to slip rings allowed its use as a three phase rotary, and it was connected to the half-frequency generator thru a three

wire line running under the floor. The rotary convertor as well as the synchronous generator and the direct current motor were supplied with field rheostats.

The ammeters and wattmeters used were of the dynamometer type made by the Weston Electric Instrument Company of Newark, New Jersey, while the voltmeters were of the Thomson electro dynamometer type as manufactured by the General Electric Company. The pressure leads of the wattmeters were connected thru double throw switches so that one wattmeter might be used for measuring the power in a balanced 3 phase circuit with power factor between unity and .5.

For pure resistance load the three leads from the half-frequency motor were taken to the corners of three lamp banks arranged in delta.

EXPERIMENTAL WORK.

Before the actual tests could be started a considerable amount of preliminary work had to be done to determine the suitability of the apparatus available in the laboratory, and to be sure that all connections were properly made. This included the proper arrangements of the leads to the upper terminal blocks of the half-frequency generator and of the synchronous generator, both of which machines had stator windings and connections just alike. The stator leads were brought out to twelve jacks in the lower terminal block and connections were made to the upper block for delta as shown in Fig. 1, and for Y as shown in Fig. 2, Page 12 .

The next thing was the determination of the voltage ratios between rotor and stator of the half-frequency machine when running under operating conditions. Its rated speed at 60 cycles was 1200

r.p.m., so accordingly it was driven at 1200 r.p.m. while 68 volts at 30 cycles were impressed upon the stator from the synchronous generator, the three phase delta connections being used on both machines. The voltage used, namely 68 volts, was chosen because this gave 110 volts on the d.c. side of the rotary convertor, the object being to consume the d.c. power in 110 volt lamp banks. Under the conditions described the electromotive force between any two slip rings of the half-frequency generator was measured, and was 38 volts in all three cases. It was then apparent that transformers would have to be used to bring the rotor and stator voltages together.

The transformers were then changed by the addition of extra turns, and were carefully tested to make sure that the extra turns as well as the regular coils were so connected that the three could be used as a three phase Y auto-transformer, Fig. 3, Page 13 .

The first test carried thru was that in which the half-frequency generator supplied power to the three lamp banks arranged in delta as shown in Fig. 4, Page 14 . A constant frequency of 30 cycles was maintained with the synchronous generator and its direct current field excitation was maintained constant. At each load the driving torque of thehalf-frequency generatorwas adjusted so that the synchronous generator supplied a minimum current, this current being that required for excitation of the half-frequency machine. In this test, as in the following ones, the current coil of the wattmeter was put in the middle of the three wires of the circuit and the potential coil connected to either of the two outside wires by means of a double throw switch. Care was taken that the wattmeters were so connected that the readings were positive when power was transfered in the direction showed by the arrows. As the power factor rarely falls below one half no special provision was made for rever-

sing the potential coil terminals. As the load was balanced in all cases, but one ammeter and one voltmeter were used at each point where readings wereto be taken.

The second test was the one most productive of satisfactory results. In this case the synchronous generator was first started in order to supply a frequency and an exci tation to the half-frequency machine, which then had its driving torque increased while that of the synchronous machine was decreased. The result of these movements was that the synchronous machine became a synchronous motor while at the same time it supplied the leading current necessary for the excitation of the half-frequency generator; the synchronous motor then furnished mechanical power to the Bullock d.c machine to which it was belted and so pumped power back into the laboratory bus bars. An ammeter in the direct current circuit showed the direction and amount of the transfer of power. In this way the half frequency generator delivered a very considerable power output. At first there was trouble with the cross currents set up by the rapid hunting due to loose belts, a current that was of too high a frequency to make the ammeter needle vibrate, and that was reduced to zero by tightening the belts to the proper tension. The apparatus was used as in Fig. 5, Page 15.

A third test was made in which the half-frequency generator supplied power to the rotary convertor, which in its turn fed banks of incandescent lamps. The exciting current for the half-frequency machine was supplied by the rotary itself. The construction of the rotary was such that its hunting action was excessive and it was found impossible to make it carry more than the load it should. For this reason the data for this test were discarded.

In addition to the above, a number of readings were taken to determine the various characteristics of the machines used. The impedance of the half-frequency generator was found by locking and short circuiting the rotor and impressing upon the stator 3 phase voltages to force thru the stator windings currents up to about twice full load. As each current was reached the circuit was opened and the voltage observed. The current was supplied by the synchronous generator at 30 cycles, both machines being connected in delta. In order to get an average value regardless of relative position of rotor and stator teeth this test was made with the rotor in three different positions.

DISCUSSION OF DATA.

In all cases the leading current supplied by the synchronous machine is larger than normal because it must overcome the lagging magnetizing current of the transformers. In a machine designed to be used as a half-frequency generator the stator and rotor voltages should be the same, and this source of trouble would be eliminated.

In all the tests the normal flux density of either the synchronous or half-frequency machines was not exceeded so that errors due to working at or above saturation are not included.

During the test in which the synchronous machine ran as a motor, Fig. 5, there was a slight unavoidable change in speed due to the ~~very~~ heavy load put upon the 5 horse power Westinghouse motor but it was not more than 3 % and the value of the results is not changed.

The large number of meters used, and the limitations of

the laboratory equipment made it impossible to use cailbrated instruments or to use the same ones in the same positions during the different tests, so that some small inconsistencies in the data may be expected.

CONCLUSIONS

On a non-inductive load the half-frequency generator is not a satisfactory machine to use,as the test with the lamp load shows that by far the larger part of the energy is furnished by the synchronous alternator which is supposed to be only an exciter. Any half-frequency generator so operating would ofcourse be out of the question as it would be very expensive for a given kilowatt output; one feature in its favor is that it has an external characteristic similar to that of a direct current shunt wound dynamo and so would be uninjured by a severe overload; the exciter, however, unless well protected by circuit breakers would receive violent treatment.

The field best suited to the half-frequency generator seems to be the supply of power to a synchronous motor that may be overexcited and so made to carry a wattless leading current. From curve sheet No. 2 it is seen that under these conditions the generator will deliver a kilowatt load approaching the kilovolt-amperes for which it is designed. Thruout the working range the rotor and stator deliver very nearly equal amounts of power,and the rate of increase of power delivered is the same in both cases. The half-frequency machine should not work at low loads as the power factor decreases with the output, and the armature heating would be high, resulting in a low

efficiency. At best, however, the power factor on the system on which it is used will be low. The regulation of the machine is poor, thus limiting its use to motor generator sets or to rail way rotary convertors in which the effect of poor regulation is minimized.

An objection to the half-frequency generator is that it requires slip-rings that carry large currents, but when the rotor and stator divide the load evenly the rings carry but half the load and considerably less than half the current as may be seen from curve sheet No. 2.

In general, the success of the half-frequency generator in commercial service seems doubtful. It would indeed be possible to secure a slightly greater turbine economy than with the synchronous generator, but its poor power factor is against it. In service where a low power factor is not an insurmountable obstacle it would be forced to compete with the induction generator, a machine cheaper to build, of more robust construction because the rotor conductors are copper bars as in a squirrel cage induction motor, and without moving contacts. At all events it would be made only in moderate sizes, as in large machines a high peripheral turbine velocity is obtainable without exceeding a rotative speed of 750 or 1000 r.p.m. These conclusions are based on the tests of a small machine designed for another purpose, and so may be open to doubt, but it is believed that the results are sufficiently decided in their character to warrant their truth.

Terminal Block Connections
Half Frequency & Synchronous Machines

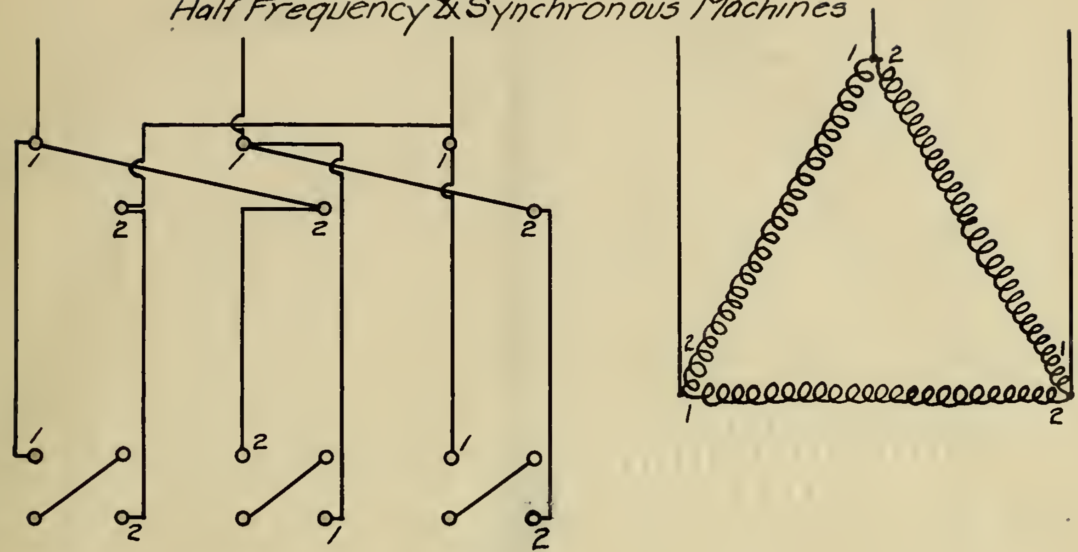


Figure 1
For Delta

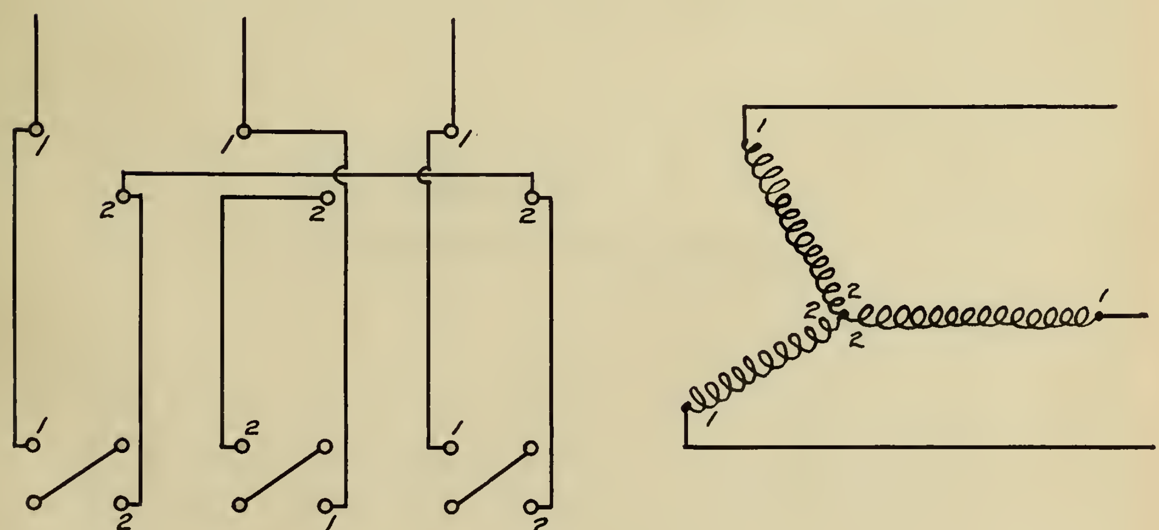


Figure 2
For Y

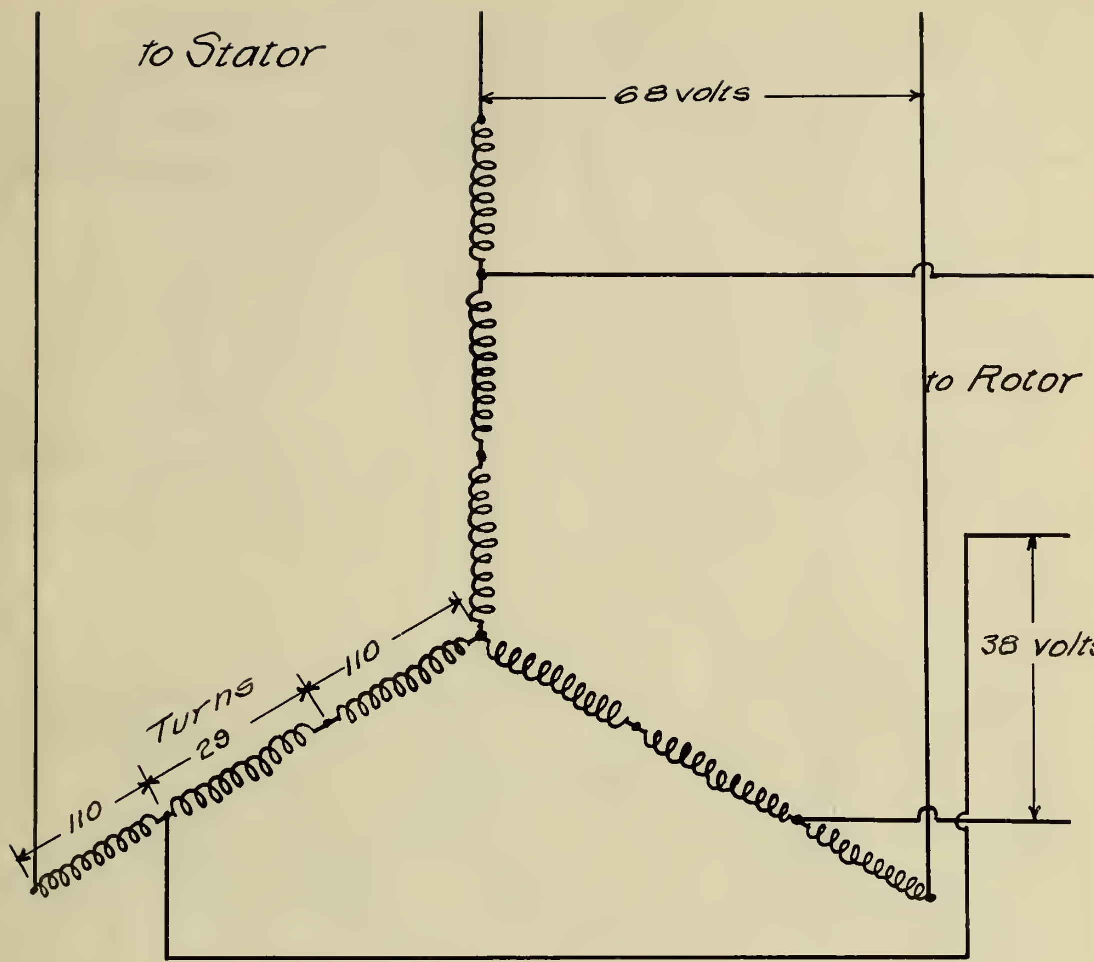
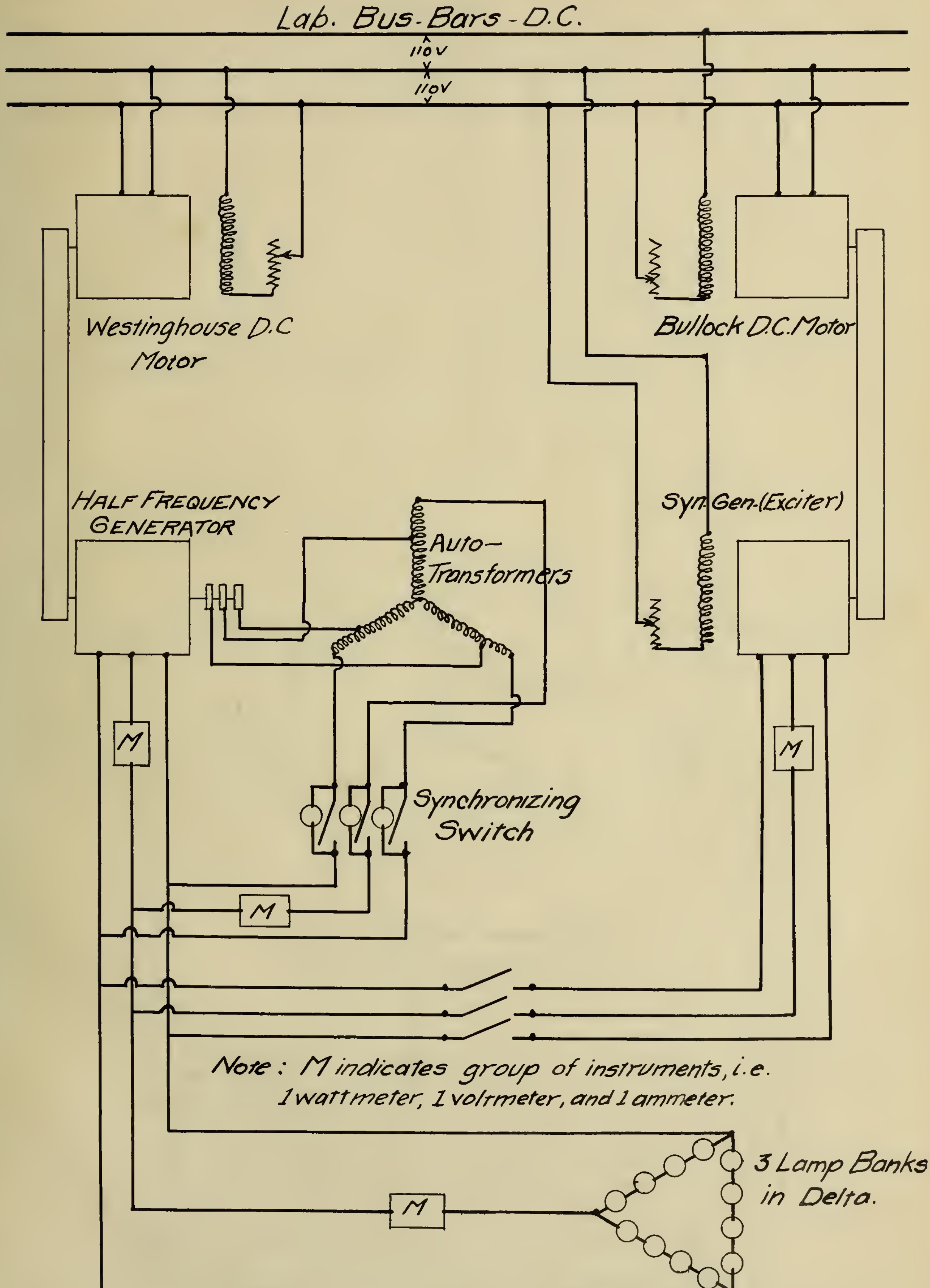


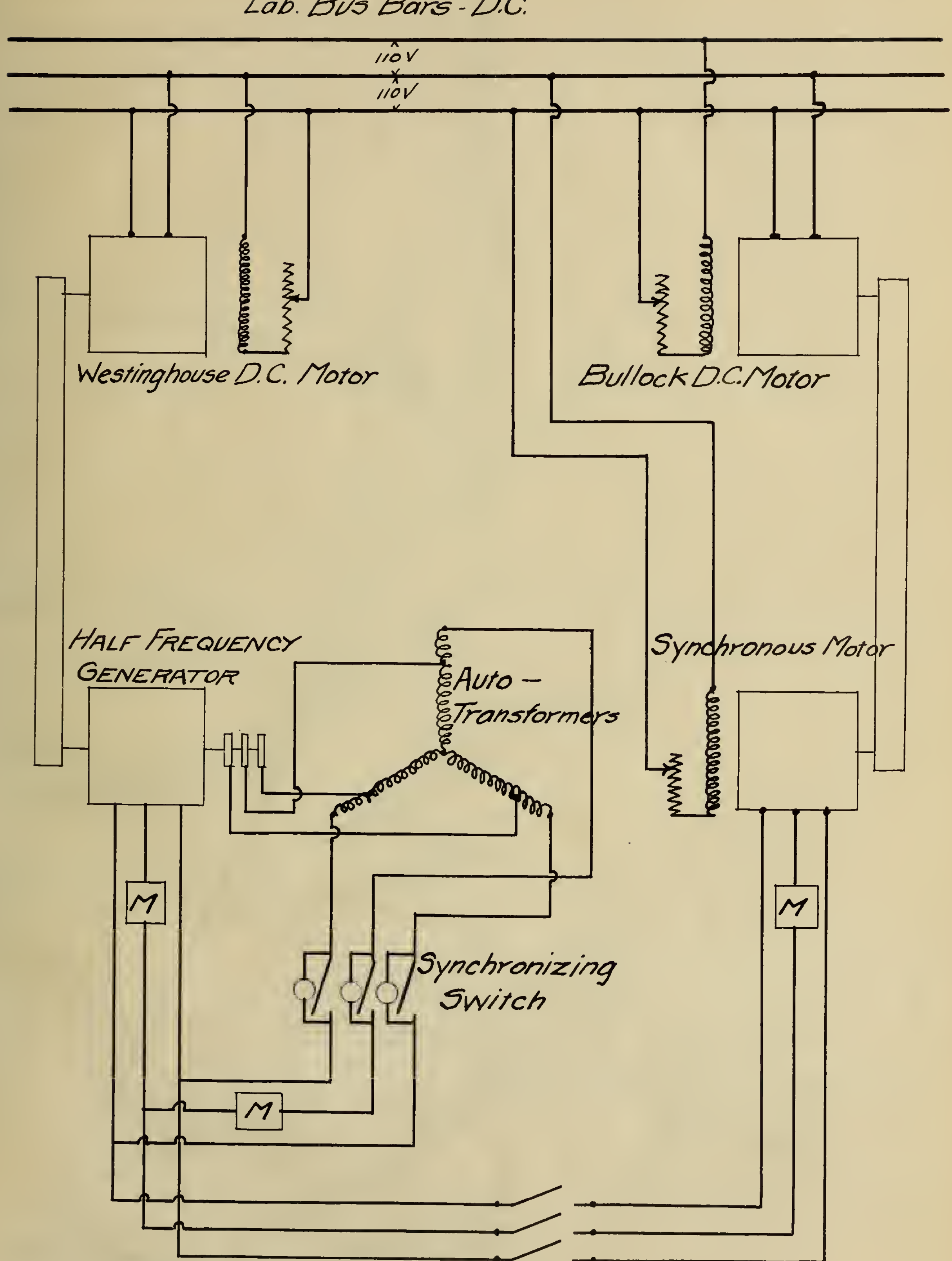
Figure 3
Transformer Connections

Figure 4

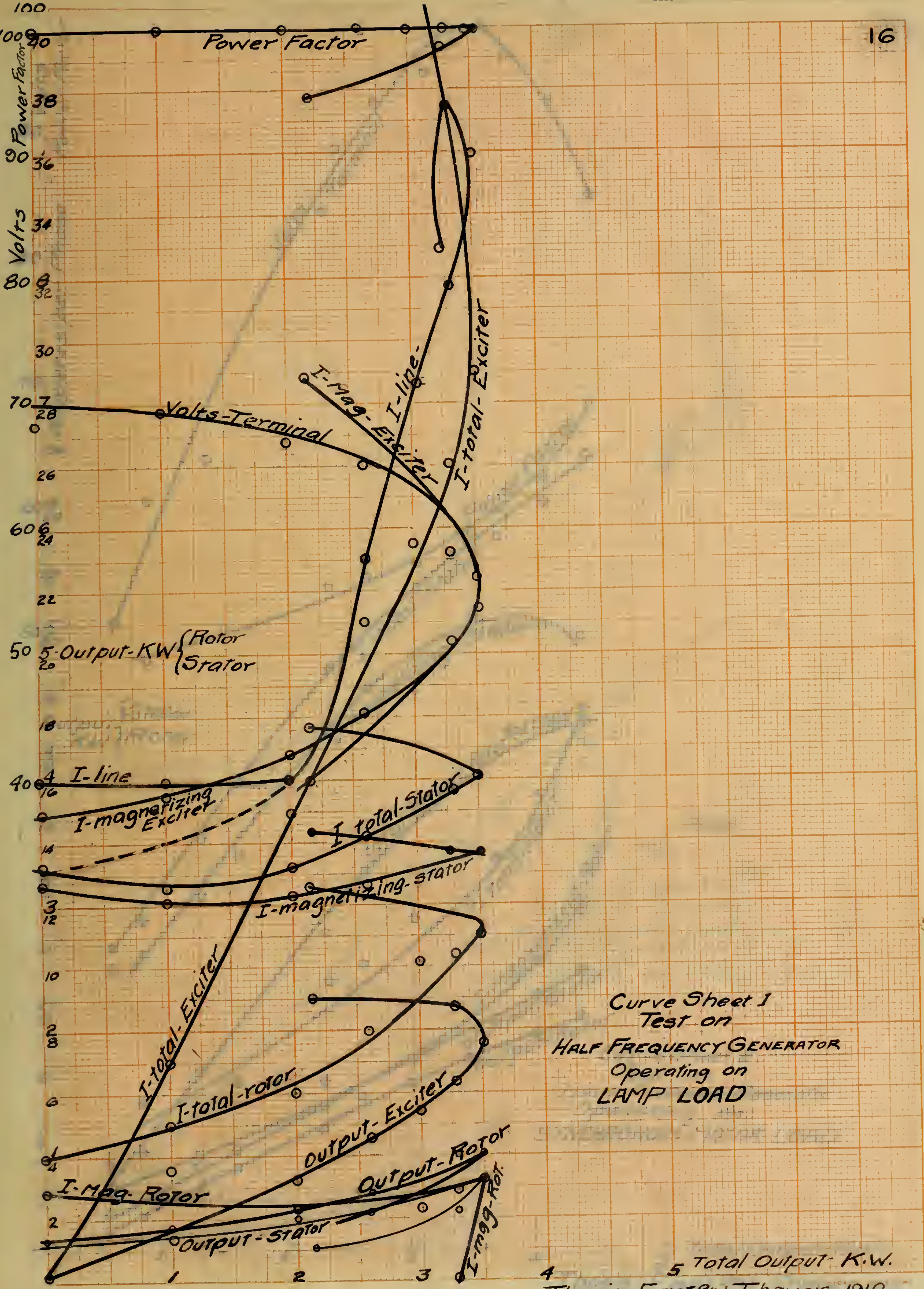


Thesis: East and Thayer-1910

Figure 5

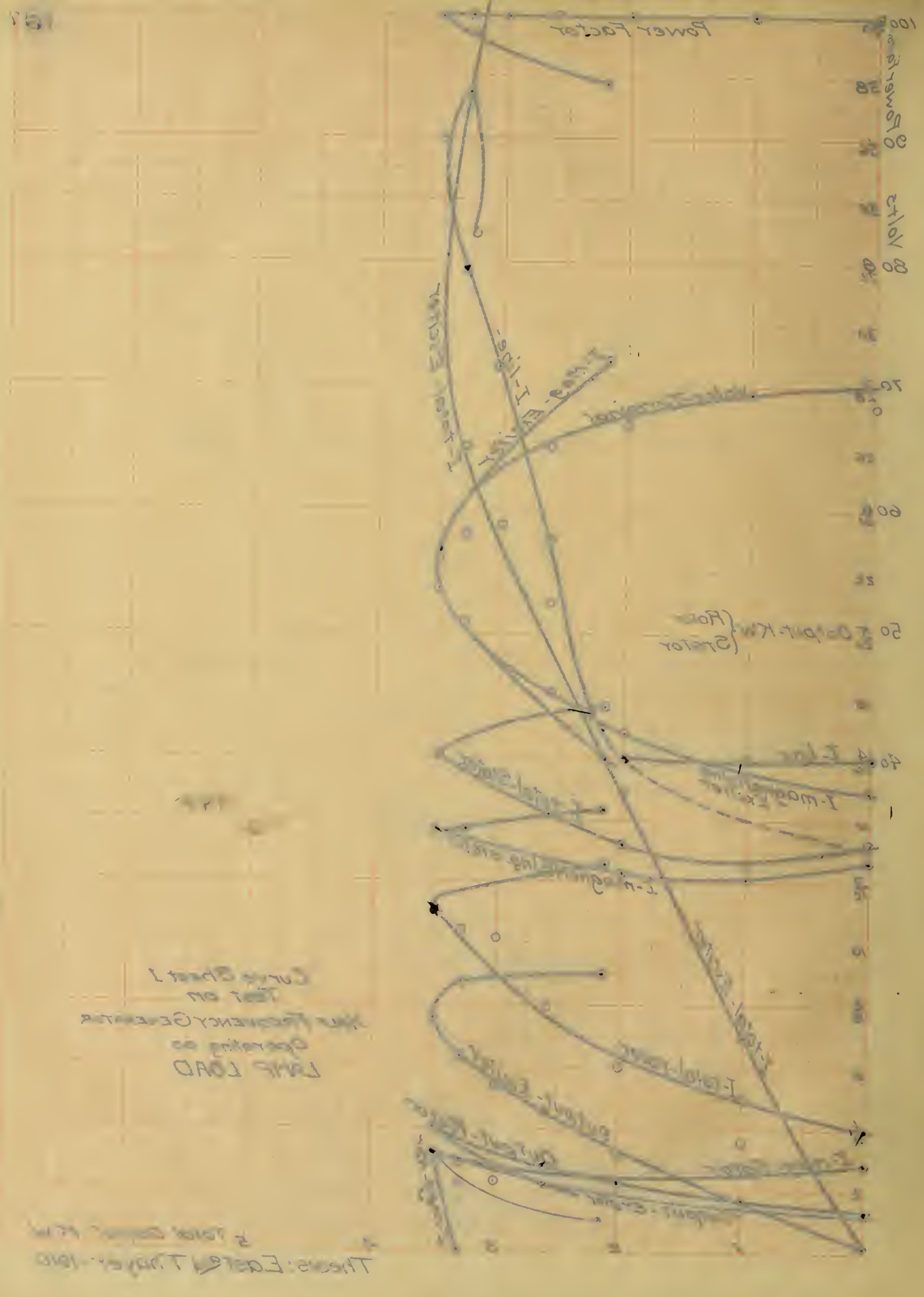


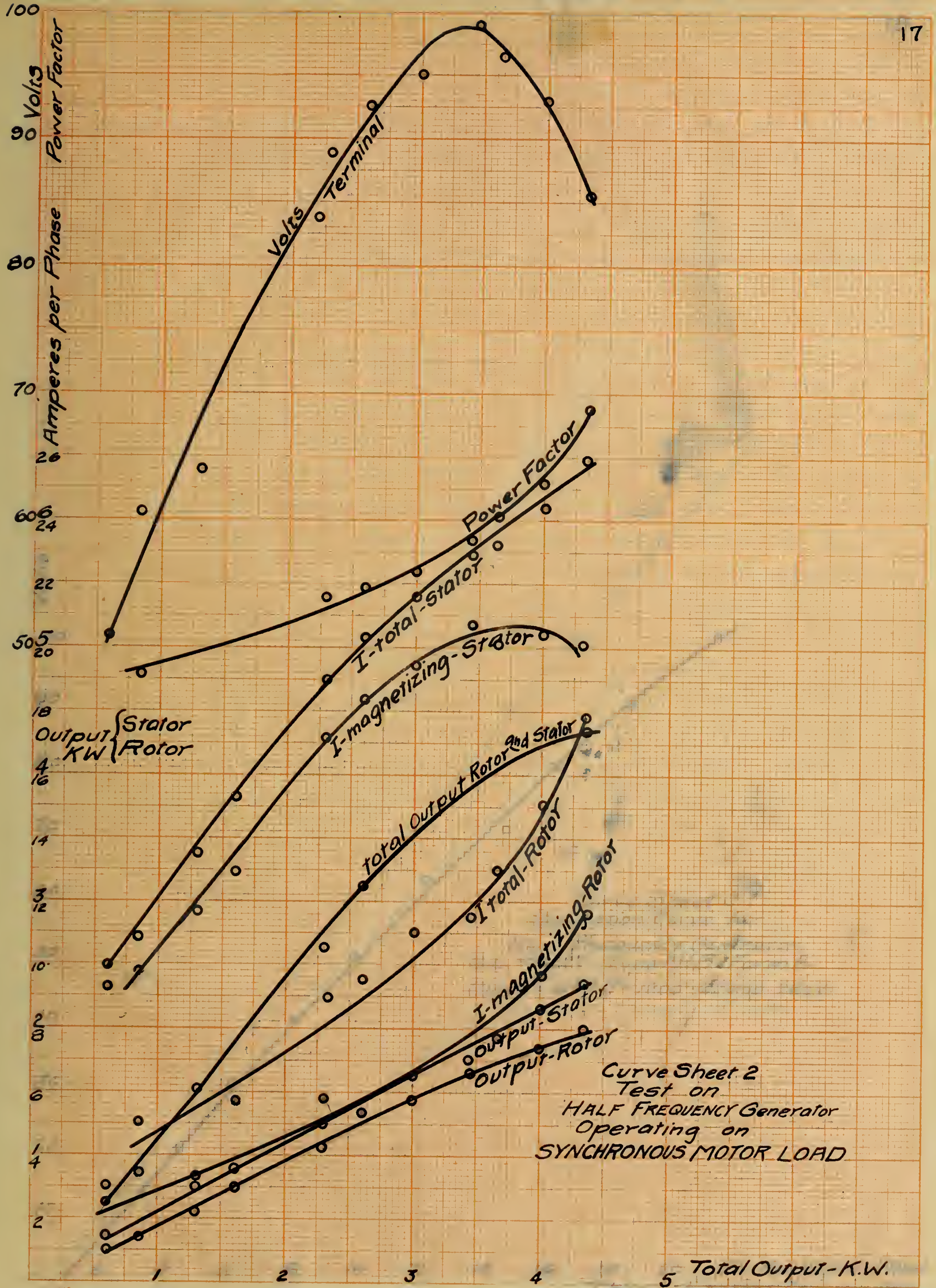
Note: M indicates group of instruments, i.e.
1 wattmeter, 1 voltmeter, and 1 ammeter.



Curve Sheet 1
Test on
HALF FREQUENCY GENERATOR
Operating on
LAMP LOAD

Thesis: East and Thayer - 1910

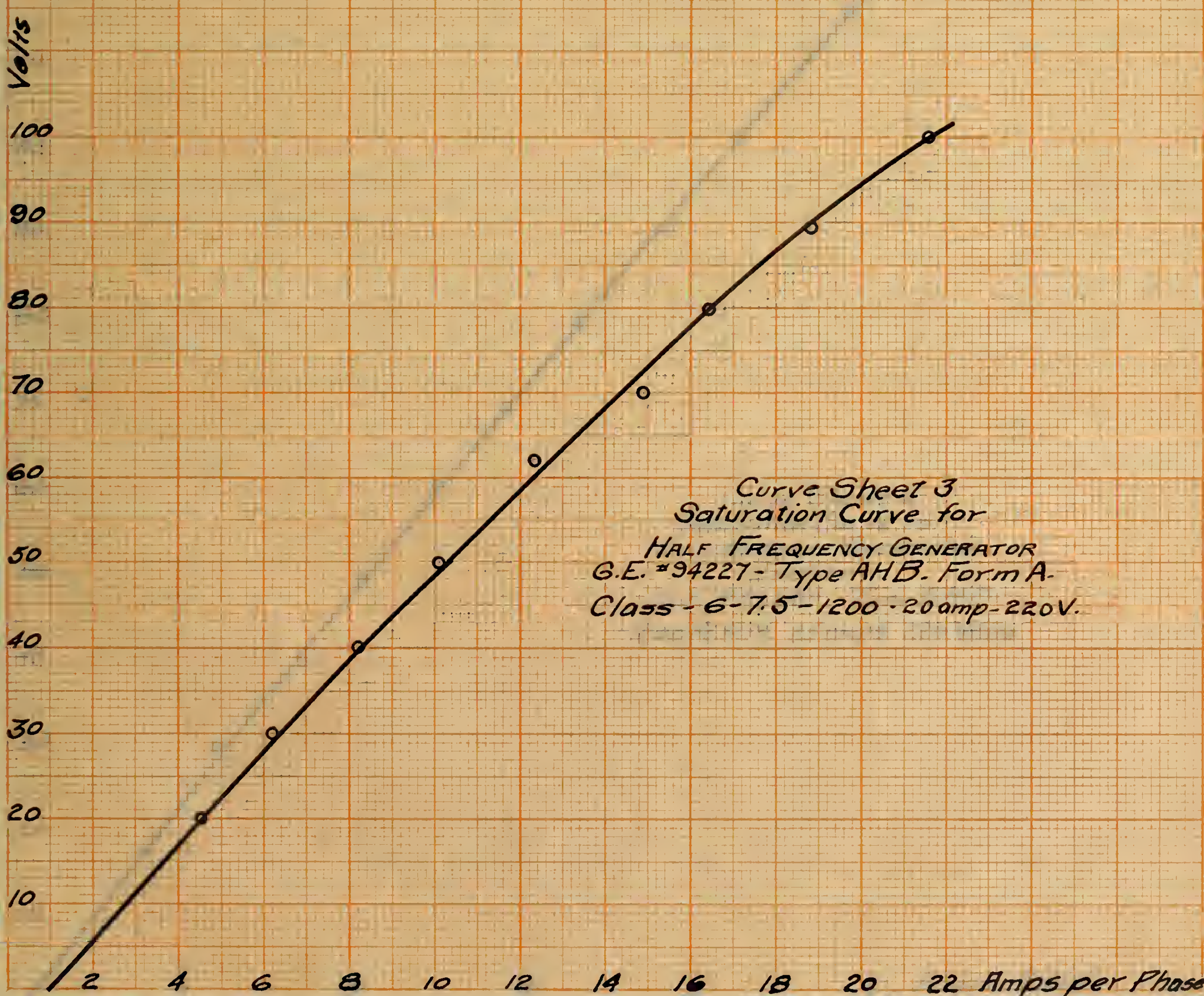

Power Factor
Curve Sheet I
Test on
New Frequency Generator
Operating on
LAMP LOAD
Thesis: Easton Thayer 1910



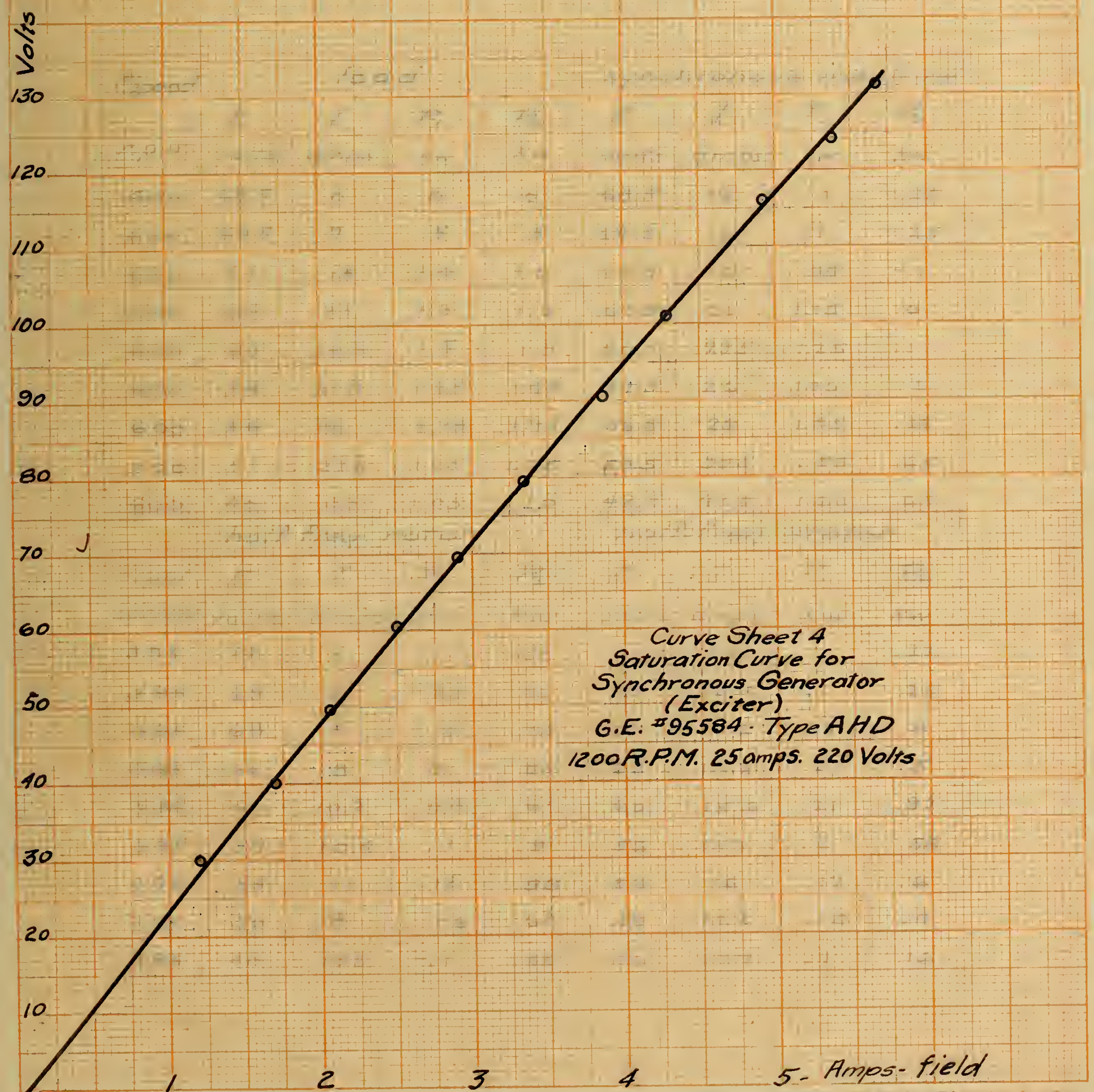
Curve Sheet 2
Test on
HALF FREQUENCY Generator
Operating on
SYNCHRONOUS MOTOR LOAD

Thesis: East and Thayer-1910

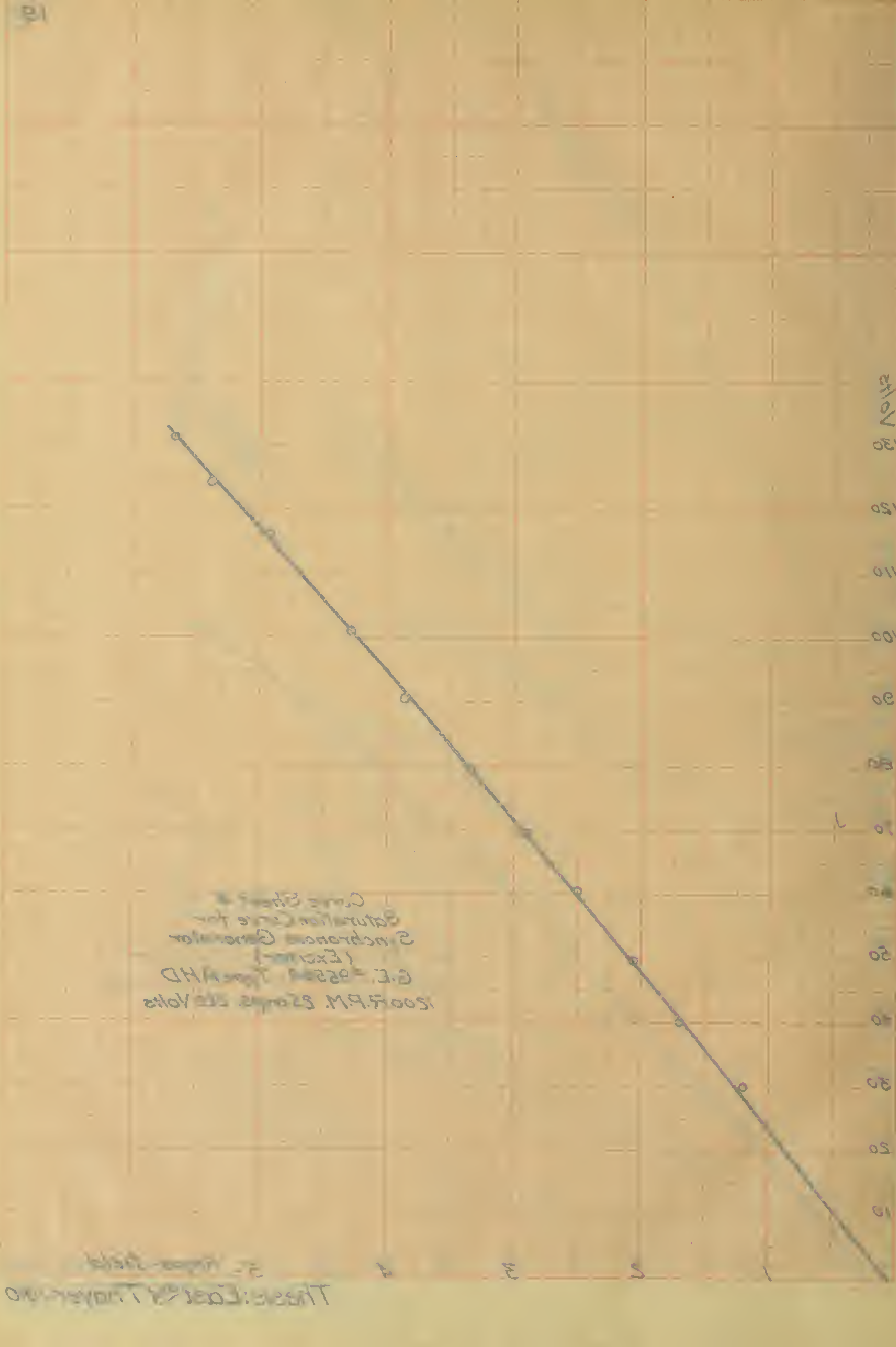
Curve Sheet 2
Test on
Half Frequency Generator
Operating on
Synchronous Motor Load
Total Output - K.W.
Thesis - Elder and Thayer - 1910



Thesis: East and Thayer-1910



Thesis: East and Thayer - 1910



Volts
130
120
110
100
90
80
70
60
50
40
30
20
10
1
2
3
4
5
Curve Sheet #
Saturation Curve for
Synchronous Generator
(Exciter)
G.E. #95584 Type M.H.D
1200 R.P.M. 25 amps. 220 Volts

Test data for lamp load

Speed	load				synchronous machine			
	E	I	P_1	P_2	E	I	P_1	P_2
r.p.m.	volts	amps	kw	kw	volts	amps	kw	kw
600	68.5	0	0	0	68.5	16	.3	-.25
600	69.5	7	.5	.5	66.5	16	.7	-.25
600	67	15	1.0	1.0	65.5	16	.95	-.1
600	65	23	1.3	1.3	63.5	21	1.15	0
600	60	28.5	1.5	1.5	60.5	23.5	1.25	.1
600	58	31.8	1.65	1.65	57.5	26	1.40	.2
600	56	36	1.75	1.75	56.5	29	1.55	.35
600	51	37.5	1.65	1.65	49.5	30.5	1.55	.65
600	40	33	1.05	1.10	42.5	42.0	1.60	.65
	half-freq. rotor				half-freq stator			
Field	E	I	P_1	P_2	E	I	P_1	P_2
current	volts	amps	kw	kw	volts	amps	kw	kw
3.95	72	4	-.3	.65	72	13	.1	.22
3.95	69	5	-.25	.66	69	12.5	.1	.25
3.95	68	6	-.15	.74	67	13.2	.17	.4
3.95	64	8	0	.85	63	14.2	.21	.5
3.95	61	10.2	.08	.61	60	15.4	.21	.93
3.95	57	10.4	.1	.9	56	15.7	.2	.58
3.95	55	11	.12	.88	54	16	.17	.6
3.95	50	8	.06	.68	49	14.2	.14	.4
3.95	40	12.5	-.1	.45	40	17.7	.1	.16

Computations for lamp load test

load				synchronous machine			
P	KVA	power	I_{mag}	P	KVA	power	I_{mag}
kw		factor	amps	kw		factor	amps
0	0	-		.05	1.780	.028	14.9
1.0	.844	1		.45	1.845	.244	15.5
2.0	1.74	1		.85	1.817	.467	14.1
2.6	2.59	1		1.15	2.31	.497	18.1
3.0	2.96	1		1.35	2.46	.598	19.6
3.3	3.19	1		1.60	2.59	.617	20.5
3.5	3.50	1		1.90	2.84	.668	21.5
3.3	3.31	.99		2.20	2.61	.842	16.4
2.15	2.29	.94		2.25	3.09	.727	28.8
rotor				stator			
P	KVA	power	I_{mag}	P	KVA	power	I_{mag}
kw		factor	amps	kw		factor	amps
.35	.499	.701	2.81	.33	1.620	.200	12.7
.41	.598	.685	3.64	.35	1.495	.233	12.1
.59	.702	.841	3.23	.57	1.535	.371	12.3
.85	.889	.957	2.31	.71	1.550	.457	12.6
.61	1.079	.565	9.2	1.14	1.604	.710	10.9
1.00	1.027	.975	2.3	.78	1.525	.511	13.5
1.00	1.048	.955	3.25	.77	1.498	.514	13.7
.74	.694	1.00	0	.54	1.181	.483	12.4
.55	.867	.634	10.64	.26	1.228	.211	14.4

Test data for synchronous motor load

half-freq. rotor				half-freq. stator			
E	I	P_1	P_2	E	I	P_1	P_2
volts	amps	kw	kw	volts	amps	kw	kw
51	3	.05	.2	52	10	-.05	.4
60.5	5	.05	.3	61	11.8	-.1	.6
64	6	.15	.4	65	13.5	0	.75
62	9	.2	.55	62	15.3	0	.87
88	9	.3	.75	88	19	-.1	1.35
92.5	9.5	.35	.9	92.5	20.3	-.15	1.5
95	11	.45	1.0	95	21.6	-.1	1.65
99	11.5	.5	1.2	99	22.9	-.1	1.85
96.5	13	.5	1.25	96.5	23.2	0	1.9
93	15	.5	1.35	93	24.4	.2	1.95
85.5	17.8	.5	1.5	85.6	26	.35	2.0
98	14.2	.55	1.4	98	24.3	.15	2.05
98	12.6	.53	1.3	98.5	23.3	0	1.95

synchronous motor					d.c. generator		
E	I	P_1	P_2	field current	E	I	P
volts	amps	kw	kw	amps	volts	amps	kw
51	14	-.12	.5	2.8	105	0	0
60	16	0	.77	3.4	107	2	.21
63.5	20	.05	1.12	3.75	106	5	.53
61	24	.15	1.25	3.92	106	8	.85
87	27	.10	2.00	5.3	108	12.5	1.35
91	29	.125	2.25	5.6	108	15	1.62
94	31	.20	2.62	5.8	104	18	1.87
98	34	.30	3.0	6.02	105	21	2.21
94	36	.40	3.05	6.00	107.5	23	2.47
90.5	39	.50	3.20	5.9	107	25	2.68
82	43.5	.62	3.50	5.85	104	27.5	2.86
96	38	.50	3.30	6.1	102	25	2.55
97	36	.35	3.00	6.0	102	22.5	2.29

Computations for synchronous motor load

rotor				stator			
P	KVA	power	I_{mag}	P	KVA	power	I_{mag}
kw		factor	amps	kw		factor	amps
.25	.265	.943	1.00	.35	.902	.388	9.22
.35	.525	.667	3.73	.70	1.248	.561	9.78
.55	.665	.826	3.38	.75	1.521	.493	11.78
.75	.968	.765	5.78	.87	1.646	.529	12.98
1.05	1.372	.766	5.77	1.25	2.89	.432	17.15
1.25	1.521	.822	5.39	1.35	3.24	.417	18.44
1.45	1.802	.804	6.54	1.55	3.55	.437	19.45
1.7	1.970	.863	5.81	1.75	3.93	.446	20.70
1.75	2.172	.806	7.70	1.90	3.87	.503	20.10
1.85	2.420	.764	9.70	2.15	3.93	.547	20.45
2.00	2.64	.758	11.65	2.35	3.69	.636	20.10

synchronous motor		
P	KVA	power
kw		factor
.60	1.167	.514
.85	1.773	.479
1.30	2.186	.595
1.62	2.614	.620
2.30	4.262	.540
2.60	4.76	.547
3.00	5.35	.560
3.45	5.90	.584
3.65	6.04	.604
4.00	6.35	.630
4.35	6.33	.688

Half-Frequency generator saturation curve

per phase		
E	I	f
volts	amps	cycles
20	4.5	30
30	6.2	30
40	8.2	30
50	10.1	30
62	12.3	30
70	14.9	30
80	16.4	30
89.5	18.8	30
100	21.6	30

Synchronous generator saturation curve

I_f	E	f
amps	volts	cycles
1.2	30	30
1.7	40	30
2.05	49.5	30
2.5	60.5	30
2.9	69.8	30
3.35	79.7	30
3.87	91.0	30
4.28	101.0	30
4.93	116.0	30
5.4	124.0	30
5.67	131.5	30